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Applying the Convention on Biological Diversity Pathway Classification to alien species in Europe

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Abstract
The number of alien species arriving within new regions has increased at unprecedented rates. Managing the pathways through which alien species arrive and spread is important to reduce the threat of biological invasions. Harmonising information on pathways across individual sectors and user groups is therefore critical to underpin policy and action. The European Alien Species Information Network (EASIN) has been developed to easily facilitate open access to data of alien species in Europe. The Convention on Biological Diversity (CBD) Pathway Classification framework has become a global standard for the classification of pathways. We followed a structured approach to assign pathway information within EASIN for a subset of alien species in Europe, which covered 4169 species, spanning taxonomic groups and environments. We document constraints and challenges associated with implementing the CBD Pathway Classification framework and propose potential amendments to increase clarity. This study is unique in the scope of taxonomic coverage and also in the inclusion of primary (independent introductions to Europe) and secondary (means of dispersal for species expansion within Europe, after their initial introduction) modes of introduction. In addition, we summarise the patterns of introduction pathways within this subset of alien species within the context of Europe.
Based on the analyses, we confirm that the CBD Pathway Classification framework offers a robust, hierarchical system suitable for the classification of alien species introduction and spread across a wide range of taxonomic groups and environments. However, simple modifications could improve interpretation of the pathway categories ensuring consistent application across databases and information systems at local, national, regional, continental and global scales. Improving consistency would also help in the development of pathway action plans, as required by EU legislation.

Keywords
accidental introduction, alien species, deliberate introduction, pathways, secondary spread

Introduction

Over the last decade, there has been considerable improvement in understanding macro-ecological determinants of biological invasions (Pyšek et al. 2020b), their impacts (Vilà et al. 2011; Hulme et al. 2013; Katsanevakis et al. 2014; Kumschick et al. 2015; Galanidi et al. 2018; Bradley et al. 2019; Magliozzi et al. 2020) and their management (e.g. Robertson et al. 2020; Csiszár and Korda 2017; Dufour-Dror 2013). Increasing availability of regional inventories of alien species has been instrumental for testing invasion theories and hypotheses at local, national, regional, continental and global scales, all with the shared ambition to provide macroecological generalisations, for instance across taxonomic groups, environments and habitats (e.g. Pyšek and Richardson 2010, Pyšek et al. this volume). For Europe, the compilation of information on more than 12 000 alien species from a wide range of taxonomic groups, through the EU-funded project Delivering Alien Species Inventories for Europe (DAISIE 2009; hereafter called the DAISIE project; data now available on GBIF, www.gbif.org), has been the basis of many broad scale analyses. This also includes the accumulation rates of alien species over time (Hulme et al. 2009) and the role of past and present environmental and economic factors in determining regional alien species richness (Pyšek

et al. 2010; Essl et al. 2010) or interplay of invasions and extinctions leading to the homogenisation of regional floras (Winter et al. 2009). The DAISIE project and its database, have subsequently contributed to assessments at the global scale, including analyses of trends of increase of naturalised species (Seebens et al. 2017) and distribution patterns of alien species across the globe (van Kleunen et al. 2015; Dawson et al. 2017; Pyšek et al. 2017).

It has been repeatedly suggested that one of the most effective strategies to prevent new introductions of invasive alien species (IAS) and, hence, to limit future costs to society and protect biodiversity and ecosystems, is through the management of major (or "priority") pathways and corresponding vectors (Carlton and Ruiz 2005; Hulme 2009; Pyšek and Richardson 2010; Ojaveer et al. 2018; Tsiamis et al. 2020). Information on the native range of the species and pathways of introduction often accompany checklists of alien species (e.g. Garcia-Berthou et al. 2005; Nentwig 2007; Minchin et al. 2013; Katsanevakis et al. 2015). Therefore, this represents an opportunity to assess and compare the relative importance of pathways across environments and taxa (Wilson et al. 2009; Liebhold et al. 2012; Essl et al. 2015). The probability of an alien species having impact increases with the number of pathways and some pathways are associated with introduction of more impactful alien species than others. As an example, plants introduced as contaminants are disproportionately less likely to have ecological impacts than those introduced through other pathways (Pergl et al. 2017). Pathway management is aimed at diminishing the propagule pressure of alien species (Lockwood et al. 2005, 2009; Simberloff 2009) and reflects the common wisdom that prevention and early action are more cost-effective than dealing with the consequences of introduction/invasion (Kaiser and Burnett 2010; Pluess et al. 2012).

Acknowledging the importance of assessing patterns in pathways where alien species arrive within new regions (primary introductions) or their spread following introduction (secondary spread), a standardised pathway terminology and hierarchical classification was proposed (Hulme et al. 2008). This framework has been extensively used in various studies assessing variation in pathways of introduction across different environments, taxonomic groups and ecological impacts (Katsanevakis et al. 2013; Essl et al. 2015; Roques et al. 2016; Pergl et al. 2017). Notably, the Hulme et al. (2008) classification formed the basis for the Convention on Biological Diversity (CBD) Pathway Classification framework (2014; https://www.cbd.int).

The DAISIE database, including the records of impact, pathways and associated references, was added to the European Alien Species Information Network (EASIN; Gatto et al. 2013). EASIN (https://easin.jrc.ec.europa.eu/easin) has been developed by the European Commission's Joint Research Centre (JRC; Katsanevakis et al. 2012) and supports the implementation of Regulation (EU) no. 1143/2014 on Invasive Alien Species (European Union 2014; Genovesi et al. 2015, hereafter referred to as the EU IAS regulation). EASIN initially adopted the pathway classification framework proposed by Hulme et al. (2008) and classified the pathways of the alien species included in the EASIN catalogue through members of its Editorial Board (Katsanevakis et al. 2015; Nunes et al. 2015; Tsiamis et al. 2016).

Successively, a new unified system to categorise introduction pathways of alien species was proposed by the CBD (2014) through the document UNEP/CBD/SBSTTA/18/9/Add.1 to improve the understanding of the most relevant vectors (agents that transport the alien species such as trains, containers, ships etc.) and activities of introduction of alien species. The CBD Pathway Classification framework has since become a standard for pathway terminology, which is a key requirement for interoperability and harmonisation of databases (Groom et al. 2017, 2019), risk analysis and large-scale studies (Pergl et al. 2017; Saul et al. 2017; Deriu et al 2017; Tsiamis et al. 2018; Korpinen et al. 2019), but unfortunately, there is a paucity of available information on pathways of introduction from continents other than Europe. The CBD Pathway Classification framework distinguishes pathways as either intentional or unintentional introductions or, alternatively, unaided spread of alien species. Correspondingly, these broad pathways are divided into six categories: Release; Escape; Transport – contaminants; Transport – stowaway; Corridors; and Unaided. As the level of detail required in pathway classification depends on the management goal (see Essl et al. 2015), a number of subcategories are used. The subcategories follow some of the associated economic uses, but some important areas are merged together (e.g. 'contaminant on animals' includes both contaminated animal products in the trade of fur, leather and wool and also the trade of living animals). A user-friendly technical guide to apply the CBD Pathway Classification framework, including detailed definitions with illustrative examples for assigning the different pathway subcategories, was developed (Harrower et al. 2017).

A number of pathways associated with the introduction of alien species have been well-documented. These include the ornamental horticultural trade (Dehnen-Schmutz et al. 2007a, b; Lambdon et al. 2008; EPPO 2012; van Kleunen et al. 2018), forestry (Křivánek et al. 2006; Brundu and Richardson 2016) for terrestrial plants, ballast water transport, aquaculture, ornamental trade, stocking for freshwater invaders (Gherardi et al. 2007, 2009; Nunes et al. 2015), shipping, aquaculture for marine alien species and other corridors (Galil et al. 2009; Katsanevakis et al. 2013). However, the pathways and vectors of introduction of many alien species are unknown, particularly for those that have been introduced accidentally (e.g. many arthropods; Rabitsch 2010).

The EU IAS regulation requires EU Member States to carry out a comprehensive analysis and prioritisation of the pathways of unintentional introduction and spread of invasive alien species of Union concern. This is based on the number or volume of species or the potential adverse impact caused. A description of the active pathways of introduction and spread, including where relevant vectors and commodities with which the species is generally associated, is also required for risk assessments according to the EU IAS regulation (Roy et al. 2018) and for prioritisation and pest risk analysis according to IPPC/EPPO standards (Brunel et al. 2010; Tanner et al. 2017). Pathway prioritisation analyses according to the EU IAS Regulation, using the CBD Pathway Classification framework, are already published for a number of EU countries (e.g. Belgium: Adriaens et al. 2018; Germany: Rabitsch et al. 2018; Greece: Zenetos et al. 2018; Italy: Servello et al. 2019;). However, these studies differ in their approach of

using the CBD Pathway Classification framework and the ways in which the classification has been modified, including addition of pathway categories or subcategories. In addition, many EU countries ask for detailed analysis beyond the requirement of the Regulation, including specifically the intentional pathways or species that can be regulated by policy (Pergl et al. 2016a).

In this paper, we discuss issues arising from the implementation of the CBD Pathway Classification framework, based on an expert assessment within the EASIN database, to assigning pathway information for a large subset of alien species in Europe. We summarise the patterns and trends amongst the taxon groups in this dataset, which is based on the experience gained through the process. We also discuss the potential amendments which may be required to the CBD Pathway Classification framework to improve consistency in its application. We are aware that the set of taxa is not exhaustive and does not randomly cover the full alien species pool in Europe; however, no comparable dataset is currently available that uses the primary and secondary pathways in the detailed CBD Pathway Classification framework. Therefore, this study can be considered as the first and only experience available globally and carried out on a large scale to align the pathway information of a regional database with the proposed CBD Pathway Classification framework.

Methods

Study area and assessed alien species

The study was based on review and classification of pathways for alien species in Europe as part of a study funded by the European Commission to populate the EASIN catalogue. The EASIN catalogue was established by the EU, but it covers the whole area of Europe (https://easin.jrc.ec.europa.eu/easin/Catalogue). Pathways, based on Hulme et al. (2008), were initially assigned by the Joint Research Centre (JRC) of the European Commission for selected species covering a range of taxonomic groups and environments. A proportion of the above pathways (catalogue version from 2017) did not directly map on to a single pathway within the CBD Pathway Classification framework (see comparison of CBD and EASIN subcategory comparison in Tsiamis et al. 2017). Therefore, the set of species provided by the JRC for this study was focused on species for which there was not a direct match to a single CBD pathway and where additional information is required to determine the correct CBD pathway assignment. The list of species included aliens *to* and aliens *in* Europe (*sensu* Lambdon et al. 2008) and comprised 4169 alien species, representing a 30% of the entire EASIN species catalogue (Katsanevakis et al. 2015). The alien species were classified in seven broad taxonomic groups and environment (further referred as *taxonomic/environmental groups*) and assigned to experts for evaluation (Table 1). Recognising taxonomic constraints, the large group of parasites (IPPC terminology; excluding insects) was divided into microorganism (Fungi & Pathogens) and larger organism such as nematodes. The list of assessed species included alien and cryptogenic ones (mainly marine species) whose native/alien status in the study area is not clear.

Table 1. Number of alien species included in the study (see Suppl. material 1 for the full list of species) classified by taxonomic/environmental group. EASIN species number of species within the EASIN catalogue for each taxonomic/environmental group (http://alien.jrc.ec.europa.eu/SpeciesMapper; accessed April 2020).

Taxonomic/environmental groups	No. of assessed taxa	EASIN species
Algae	129	150
Microorganisms	567	900
Marine and Freshwater invertebrates	718	2300
Nematodes	39	170
Plants	434	6600
Terrestrial invertebrates	2102	3400
Vertebrates	180	700

Pathway assignment

For each species, 3–4 experts with knowledge of the specific taxonomic/environmental groups were selected. Each expert was assigned a subset of alien species and performed searches of the scientific literature (WoS), online repositories of information on alien species (e.g. CABI Invasive Species Compendium, CABI abstracts, DAISIE database, EPPO Global Database) and grey-literature to find information on primary introduction and secondary spread pathways. For each assessed alien species, these pathways were then assigned to one or more of the CBD pathways categories and subcategories and at least one supporting reference was given for each recorded pathway. This was based on the CBD Pathway Classification guidance document that was developed during the same period (Harrower et al. 2017). Although the focus was on Europe (excluding the outermost regions of the EU Member States), introduction pathway information from other regions in the world or, in some cases, pathway information not linked to any specific region, was used to infer potential pathways of entry to, and/or spread within Europe. Similarly, where information was lacking for the assessed species, pathway information for closely-related species was used to infer pathways.

Primary and secondary (spread) pathways

As many alien species spread within or between neighbouring regions through secondary pathways, which often differ from the primary ones, each assessor had to distinguish between the primary and secondary pathway(s). Primary pathways in this study covered all independent introductions to Europe from regions of their native range and also from regions outside Europe where they are alien. Secondary pathways cover means of dispersal or transfer of species between country/regions where the species is non-native after introduction through the primary pathway(s) (i.e. from a European country/region where the species is alien to another European country/region where it is also alien, but was not previously present). The primary pathways were not applied to species with both a native and alien range within Europe (alien *in*) because the assignment of pathways was at the European scale.

Levels of confidence

In addition to the pathway assignments, experts were asked to provide a measure of their confidence (i.e. low, intermediate or high) for each pathway assigned to an alien species. To determine the confidence related to a given pathway assignment, several aspects were considered. Two of the most important aspects were the quality of the source in which the pathway information was found and the quality and appropriateness of the evidence itself (see Fig. 1). For instance, a pathway assignment based upon information in a peer-reviewed scientific paper which report direct evidence of transport of the species by a particular vector in the target region would have a high confidence. On the other hand, an assignment, based on an expert's statement with no additional direct evidence or link to a peer-reviewed source, would be considered as low confidence.

Peer-review process

The pathways and associated confidence level assigned by an expert were subsequently reviewed by another expert from the same taxonomic/environmental group within the

Source Quality	Quality of Evidence: **High** *i.e. direct evidence of species using pathway to arrive in Europe/spread within Europe*	**Intermediate** *i.e. indirect evidence of pathway use (e.g. individuals found near botanic gardens), direct evidence of species using pathway in other regions*	**Low** *i.e. supposition based on similar species or life history of species but with no direct or indirect evidence*
High *i.e. peer-reviewed journal, grey literature by respected sources*	High	Medium	Low
Intermediate *i.e. grey literature from credible source, information from expert(s)*	Medium	Medium	Low
Low *i.e. grey literature from unknown/ non-expert authors, publications from unspecified/less credible sources*	Low	Low	Low

Figure 1. Confidence matrix illustrating the criteria for assigning levels of confidence for species pathways records. Redrawn from Harrower et al. (2017).

project team. For each pathway assignment, the reviewer could either agree with the initial expert or disagree with the assigned pathway and/or its confidence level. Reviewers were also asked to provide any comments and/or justification related to their decision. In addition to agreeing or disagreeing with the assignments made by the initial expert, the reviewers were also invited to assign new additional primary or secondary pathways for the species, if any. The final assignment to pathways and confidence levels were then reviewed by additional experts from the same taxonomic/environmental group.

Results

We were not able to provide any pathway information for 327 fungi and pathogens, 51 terrestrial arthropods, eight aquatic invertebrates (marine and freshwater) and one plant (*Carduus nutans*), because of a lack of available evidence. Therefore, the final list of species with at least one pathway was 3782. In total, the assignment of pathway information resulted in 7658 taxon/pathway combinations, supported by 2288 references (i.e. unique articles, web pages, reports). With the exception of plants and terrestrial arthropods, the number of identified secondary pathways was lower than that of primary introductions, with the greatest relative difference observed for vertebrates (Table 2).

Table 3 shows a detailed matrix for the taxonomic/environmental groups and the CBD Pathway Classification framework subcategories, divided by the primary introduction and secondary spread pathways. Amongst the release category, the subcategories, hunting and fishery in the wild (including game fishing), were only assigned to primary introductions. For the escape category, fur farms were only found in primary pathways. Contaminated bait within Transport-contaminant was not present neither in primary nor in secondary pathways. Introductions along terrestrial human-made infrastructures (tunnels and land bridges) were recorded only in secondary spread.

There was variation in the frequency of CBD Pathway Classification (sub)categories relevant to primary and secondary introduction/spread across taxonomic groups and environments (Table 3). Aquatic organisms are most commonly introduced by unintentional pathways such as stowaways, contaminants and corridors. Microorganisms and nematodes are most commonly introduced as contaminants which are also an important pathway for their secondary spread. On the other hand, plants and verte-

Table 2. Number of alien species within each broad taxonomic/environmental group assigned to introduction (primary pathway) and spread (secondary pathway).

Taxonomic/environmental groups	Primary introduction	Secondary spread
Algae	126	36
Microorganisms	221	100
Marine and Freshwater invertebrates	620	207
Nematodes	29	19
Plants	298	303
Terrestrial invertebrates	1345	1499
Vertebrates	177	15

brates are often introduced intentionally through direct release to nature and plants are additionally escaping from confinement. For most taxonomic/environmental groups, secondary spread is most commonly through Unaided /natural spread across borders and not so much intentional spread by humans (Tables 3, 4).

The confidence levels of pathway assignments varied amongst the taxonomic groups. Pathways assigned to fungi and pathogens had the highest percentage of low confidence amongst groups, whereas vertebrates, plants and parasites were typically assigned with intermediate or high confidence (Fig. 2).

Discussion

Our study highlights that the importance of different pathways differs amongst taxonomic/environmental groups and for both primary introductions and secondary spread in Europe. However, it is apparent that some of the CBD Pathway Classification framework subcategories were not used at all or were relevant for only a few species (see Table 4; e.g. contaminated bait, tunnels and land bridges). This is, in part, because the names of these pathways have been kept unchanged amongst databases. Consequently there was a high probability of a direct match from the original EASIN pathway classification scheme to the CBD Pathway Classification framework (and, thus, these species did not appear in our assessment).

The ease of assigning pathway information using the CBD Pathway Classification framework depends on the availability of information. For many species, there was limited evidence available and many records were based on grey literature sources and consequently were assigned low confidence. This is highlighted also by Faulkner et al. (2020) who identified that the complexity of the CBD Pathway Classification framework when compared with the classification of Hulme et al. (2008) may cause some problems. The potential bias due to limited knowledge of species-pathway association was transparently documented by assigning confidence levels and a three-step process of peer-review. The confidence was generally higher for the taxa having a higher number of well-documented intentional introductions, such as vertebrates and plants, than for those species introduced unintentionally.

We are aware that the pre-selection of the species in this study may introduce biases. The dataset described in this study has a limited coverage of some large taxonomic groups (e.g. only about 400 species of plants were included from the 6600 species within the EASIN catalogue). Nevertheless, this pathway dataset covers about one third of the alien flora and fauna of Europe and so, we believe, the observed patterns of pathways have wide relevance. Furthermore, the analysis presented is limited by the fact that the pathways were not prioritised according to their relative importance, for example, in terms of rates of introduction or propagule number, because of lack of robust data. In addition, the importance of specific pathways can vary regionally and temporally (Pyšek et al. 2011, Roques et al. 2016). The discrepancy between the number of assessed species (Table 1) and presented primary and secondary pathways (Table 2) is caused by the evidence-based approach of this study. It can be expected that "Unaided /natural spread across borders" will be common across most of the alien species included here; however, as there were no direct references, the pathway was recorded only for a few of the species.

Table 3. (part 1) Percentages within the broad taxonomic/environmental groups and numbers (in brackets) of records per taxon/pathway combinations and CBD Pathway Classification subcategories. Data are shown separately for introduction (primary pathway) and spread (secondary pathway).

	Pathway type (Hulme et al. 2008)	**Release in nature**							
	CBD Pathway Classification category	**Biological control**	**Erosion control/ dune stabilization (windbreaks, hedges, …)**	**Landscape/flora/fauna "improvement" in the wild**	**Fishery in the wild (including game fishing)**	**Hunting**	**Introduction for conservation purposes or wildlife management**	**Release in nature for use (other than above, e.g., fur, transport, medical use)**	**Other intentional release**
Primary introduction	Algae								
	Microorganisms								
	Marine and Freshwater invertebrates				0.7 (5)				
	Nematodes								
	Plants		6.5 (28)	2.8 (12)				1.2 (5)	2.3 (10)
	Terrestrial invertebrates	0.2 (4)							0.1 (2)
	Vertebrates	2.8 (5)		2.2 (4)	23.3 (42)	22.2 (40)	3.3 (6)	1.1 (2)	28.3 (51)
Secondary spread	Algae								
	Microorganisms								
	Marine and Freshwater invertebrates								0.1 (1)
	Nematodes								
	Plants		7.6 (33)	2.5 (11)				1.8 (8)	1.8 (8)
	Terrestrial invertebrates	0.2 (4)							
	Vertebrates						0.6 (1)		

Table 3. Part 1 continued.

	Pathway type (Hulme et al. 2008)	**Escape from confinement**											
	CBD Pathway Classification category	**Agriculture (including Biofuel feedstocks)**	**Farmed animals (including animals left under limited control)**	**Forestry (including afforestation or reforestation)**	**Fur farms**	**Aquaculture / mariculture**	**Botanical garden/zoo/aquaria (excluding domestic aquaria)**	**Pet/aquarium/terrarium species (including live food for such species)**	**Horticulture**	**Ornamental purpose other than horticulture**	**Research and ex-situ breeding (in facilities)**	**Live food and live bait**	**Other escape from confinement**
Primary introduction	Algae						0.8 (1)	2.3 (3)					
	Microorganisms												
	Marine and Freshwater invertebrates		0.1 (1)			1.1 (8)		1.1 (8)				0.3 (2)	
	Nematodes												
	Plants	8.1 (35)		4.6 (20)		0.7 (3)	6.2 (27)	6 (26)	10.9 (47)	46.4 (201)			0.5 (2)
	Terrestrial invertebrates		0.2 (4)					0.5 (11)			0.2 (5)		0 (1)
	Vertebrates		0.6 (1)		2.2 (4)	10 (18)	2.8 (5)	11.1 (20)				0.6 (1)	7.2 (13)
Secondary spread	Algae					0.8 (1)							
	Microorganisms	0.4 (1)											
	Marine and Freshwater invertebrates		0.3 (2)					0.7 (5)				0.6 (4)	0.1 (1)
	Nematodes												
	Plants	7.2 (31)		3 (13)		0.7 (3)	5.3 (23)	3.5 (15)	9.7 (42)	13.6 (59)	0.5 (2)		1.6 (7)
	Terrestrial invertebrates										0.2 (5)		
	Vertebrates												

Table 3. Part 2.

	Pathway type (Hulme et al. 2008)	**Transport- contaminant**									
	CBD Pathway Classification category	**Contaminant nursery material**	**Contaminated bait**	**Food contaminant (including of live food)**	**Contaminant on animals (except parasites, species transported by host/vector)**	**Parasites on animals (including species transported by host and vector)**	**Contaminant on plants (except parasites, species transported by host/vector)**	**Parasites on plants (including species transported by host and vector)**	**Seed contaminant**	**Timber trade**	**Transportation of habitat material (soil, vegetation,…)**
Primary introduction	Algae				51.2 (66)	1.6 (2)	0.8 (1)				
	Microorganisms	72.5 (174)		3.8 (9)	7.1 (17)		18.3 (44)	24.6 (59)	25.8 (62)	5.4 (13)	20.8 (50)
	Marine and Freshwater invertebrates				12.7 (90)	5.6 (40)	1.3 (9)		2.5 (18)		
	Nematodes	30.8 (12)		2.6 (1)		30.8 (12)	10.3 (4)	46.2 (18)	10.3 (4)	5.1 (2)	30.8 (12)
	Plants	0.9 (4)		0.9 (4)	2.3 (10)	0.2 (1)	0.5 (2)	0.5 (2)	14.5 (63)	0.9 (4)	3.5 (15)
	Terrestrial invertebrates	11.3 (232)		11.8 (241)	0.1 (2)	3.5 (72)	32.2 (660)	0.9 (18)	2 (42)	2.8 (57)	8.5 (175)
	Vertebrates	3.3 (6)			0.6 (1)		1.1 (2)	1.1 (2)	0.6 (1)	0.6 (1)	0.6 (1)
Secondary spread	Algae				4.7 (6)						
	Microorganisms	10 (24)			3.8 (9)	0.4 (1)	5 (12)	2.9 (7)	0.4 (1)	0.4 (1)	9.2 (22)
	Marine and Freshwater invertebrates	0.1 (1)			6.1 (43)	4.8 (34)	1.1 (8)		0.3 (2)		2 (14)
	Nematodes	15.4 (6)			7.7 (3)	30.8 (12)	7.7 (3)	7.7 (3)			25.6 (10)
	Plants	2.3 (10)		0.5 (2)	6.2 (27)	0.5 (2)	2.1 (9)	0.9 (4)	21.5 (93)	0.5 (2)	13.4 (58)
	Terrestrial invertebrates	10.3 (211)		13 (267)	0.1 (3)	3.3 (68)	35.7 (733)	0.5 (11)	2.9 (59)	5.2 (107)	10.4 (213)
	Vertebrates										0.6 (1)

Table 3. Part 2 continued.

	Pathway type (Hulme et al. 2008)	**Transport- stowaway**											**Corridor**		**Unaided**
	CBD Pathway Classification category	**Angling/fishing equipment**	**Container/bulk**	**Hitchhikers in or on airplane**	**Hitchhikers on ship/boat (excluding ballast water and hull fouling)**	**Ship/boat ballast water**	**Ship/boat hull fouling**	**Machinery/equipment**	**People and their luggage/equipment (in particular tourism)**	**Organic packing material, in particular wood packaging**	**Vehicles (car, train, …)**	**Other means of transport**	**Interconnected waterways/basins/seas**	**Tunnels and land bridges**	**Natural dispersal across borders of invasive alien species that have been introduced through pathways 1 to 5**
Primary introduction	Algae					32.6 (42)	53.5 (69)					0.8 (1)	17.8 (23)		
	Microorganisms							2.1 (5)	2.5 (6)	2.5 (6)	0.8 (2)		1.7 (4)		1.3 (3)
	Marine and Freshwater invertebrates	0.3 (2)			0.1 (1)	53.7 (381)	48 (341)		0.1 (1)			2.4 (17)	15.9 (113)		0.1 (1)
	Nematodes		5.1 (2)					10.3 (4)	17.9 (7)	7.7 (3)	10.3 (4)				
	Plants		0.2 (1)		0.7 (3)	1.8 (8)	0.2 (1)	0.9 (4)	0.2 (1)	0.9 (4)	0.9 (4)	0.9 (4)	0.2 (1)		
	Terrestrial invertebrates		2.9 (60)	0.4 (8)	4.4 (90)		0 (1)		0.3 (7)	1.7 (34)	0.9 (18)	0.2 (4)			0.1 (2)
	Vertebrates				17.8 (32)	13.3 (24)	1.1 (2)	0.6 (1)	0.6 (1)			0.6 (1)	5.6 (10)		
Secondary spread	Algae	7 (9)				5.4 (7)	15.5 (20)								15.5 (20)
	Microorganisms							1.7 (4)	1.7 (4)		1.3 (3)		2.5 (6)		20.8 (50)
	Marine and Freshwater invertebrates	1.4 (10)			0.3 (2)	12.4 (88)	7.2 (51)	2 (14)		0.1 (1)		0.4 (3)	2.3 (16)		5.9 (42)
	Nematodes		5.1 (2)					5.1 (2)	5.1 (2)	2.6 (1)	5.1 (2)				5.1 (2)
	Plants	0.2 (1)			2.8 (12)	0.7 (3)		20.1 (87)	4.2 (18)	0.9 (4)	6 (26)	3.2 (14)	2.1 (9)	0.2 (1)	19.4 (84)
	Terrestrial invertebrates		0.3 (7)	0 (1)	2 (41)		0 (1)		0.8 (17)	2 (40)	4.6 (95)	0.1 (2)	0 (1)		2.6 (54)
	Vertebrates												1.1 (2)		6.1 (11)

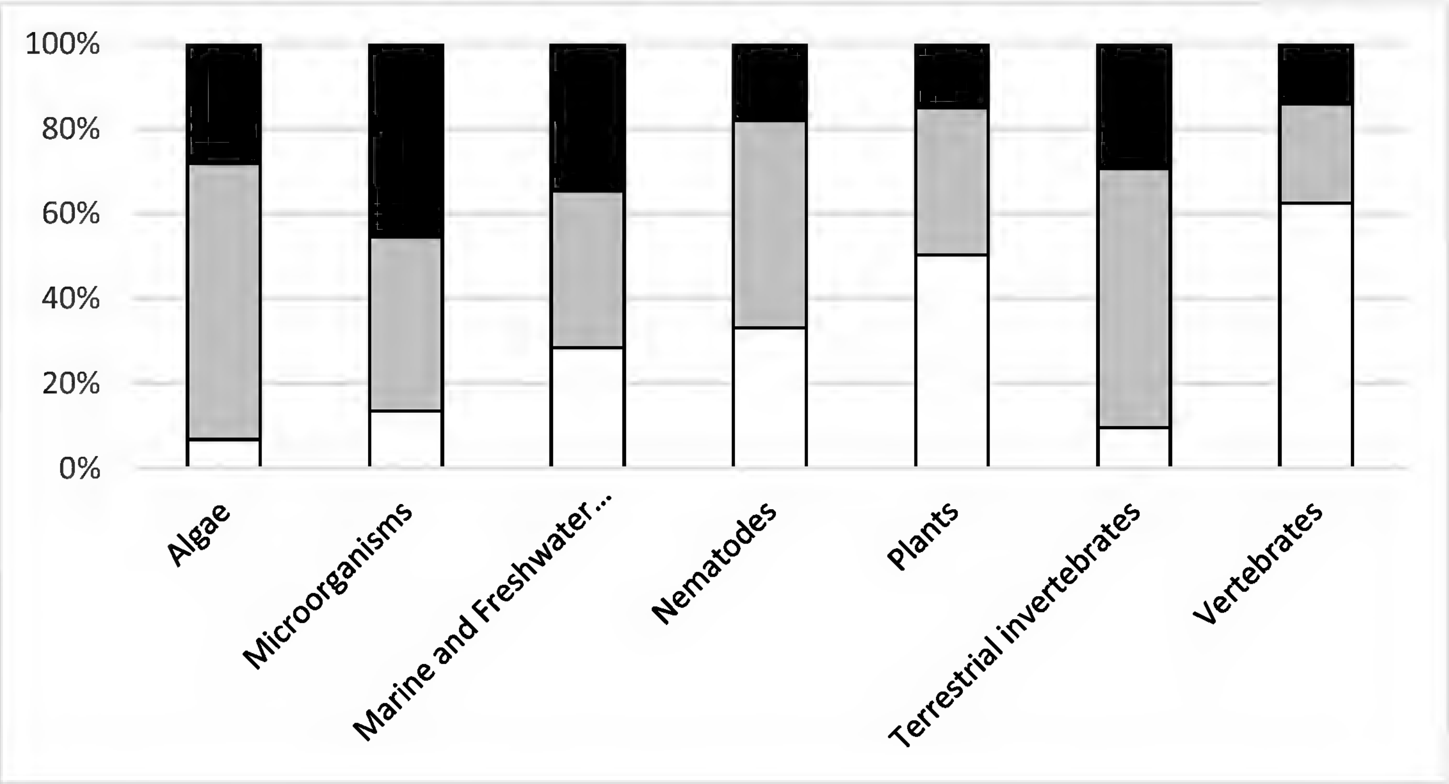

Figure 2. Percentages of species – pathway combinations assigned high (black), intermediate (grey) or low (white) confidence by the experts assigning the categories across different taxonomic/environmental groups.

Use of the CBD (sub)categories for national policies

The CBD Pathway Classification framework has value for underpinning prioritisation of pathways – to assist in development of policies and in their implementation, i.e. executing pathway management activities. It can be combined with assessments of impacts (Pergl et al. 2017; Saul et al. 2017) to prevent their introduction and manage the spread of the most invasive and harmful alien species (Meyerson and Reaser 2003; Hulme 2011). Some pathways and taxonomic groups contribute disproportionally to the overall risk from IAS (Essl et al. 2015; Pergl et al. 2017) and these should be the subject of increased attention. However, to fully assess the potential risk of each pathway, not only is the proportion of species with negative impact relevant, but also the propagule pressure (Blackburn et al. 2020), climatic match to the source region (Faulkner et al. 2017) and other factors like presence/absence of sanitary and phytosanitary measures need to be used.

The terminology in the CBD Pathway Classification framework and in other broadly-used schemes is somewhat different. Although the CBD Pathway Classification framework provides a detailed level of pathway categories and subcategories, in a number of cases, the framework lacks a clear connection to trade and policy regulation terminology. Indeed, in other systems, a well-defined terminology for trade exists (e.g. International Plant Protection Convention/International Standards for Phytosanitary Measures, the EU Combined Nomenclature for custom and trade, https://comtrade.un.org). In addition, there is a plethora of possible combinations of pathways and vectors, some of which have been described in literature with specific terms (e.g. acclimatisation societies and gardens; van Kleunen et al. 2018). Therefore, based on our experience in assigning pathway classifications and corresponding

Table 4. The three most frequently assigned CBD Pathway Classification framework subcategories associated with each broad taxonomic/environmental group for both introduction (primary pathway) and spread (secondary pathway). Rel – Release, Esc – Escape, Cont – Contaminant, Stow – Stowaway, Cor – Corridor, Un – Unaided (Hulme et al. 2008).

Taxonomic/ environmental group	Primary introduction	Secondary spread
Algae	**Stow:** Ship/boat hull fouling; **Cont:** Contaminant on animals (except parasites, species transported by host/ vector); **Stow:** Ship/boat ballast water	**Stow:** Ship/boat hull fouling; **Un:** Natural; **Stow:** Angling/fishing equipment
Microorganisms	**Cont:** Contaminant nursery material; **Cont:** Seed contaminant; **Cont:** Contaminant on plants (except parasites, species transported by host/vector)	**Un:** Natural; **Cont:** Contaminant nursery material; **Cont:** Transportation of habitat material (soil, vegetation,…)
Marine and Freshwater invertebrates	**Stow:** Ship/boat ballast water; **Stow:** Ship/boat hull fouling; **Cor:** Interconnected waterways/basins/seas	**Stow:** Ship/boat ballast water; **Stow:** Ship/boat hull fouling; Contaminant on animals (except parasites, species transported by host/vector) **Un:** Natural
Nematodes	**Cont:** Parasites on plants (including species transported by host and vector); **Cont:** Contaminant nursery material; **Cont:** Parasites on animals (including species transported by host and vector); **Cont:** Transportation of habitat material (soil, vegetation, …)	**Cont:** Parasites on animals (including species transported by host and vector); **Cont:** Transportation of habitat material (soil, vegetation, …); **Cont:** Contaminant nursery material
Plants	**Esc:** Ornamental purpose other than horticulture; **Cont:** Seed contaminant; **Esc:** Horticulture	**Cont:** Seed contaminant; **Stow:** Machinery/equipment; **Un:** Natural
Terrestrial invertebrates	**Cont:** Contaminant on plants (except parasites, species transported by host/ vector); **Cont:** Food contaminant (including of live food); **Cont:** Contaminant nursery material	**Cont:** Contaminant on plants (except parasites, species transported by host/ vector); **Cont:** Transportation of habitat material (soil, vegetation,…); **Cont:** Contaminant nursery material
Vertebrates	**Rel:** Other intentional release; **Rel:** Fishery in the wild (including game fishing); **Rel:** Hunting	**Un:** Natural; **Cor:** Interconnected waterways/basins/seas

confidence levels, to alien species within the EASIN catalogue, in the following sections, we discuss the problems encountered and propose modifications to the CBD Pathway Classification framework.

The way forward: suggestions to amend the CBD Pathway Classification framework. Modification of the CBD Pathway Classification framework subcategories and revised descriptions (Table 5)

We argue that some of the CBD Pathway Classification framework subcategories or, rather, their descriptions, are not sufficiently distinct so their delimitation and interpretation, in some cases, overlap (see also Faulkner et al. 2020). Detailed descriptions are published in the guidance document (Harrower et al. 2017). Therefore, the CBD

Pathway Classification framework has to be used jointly with this document, but to date, there appears to be a lack of evidence that this is the case from citations in scientific literature. The lack of clarity is caused by using the short subcategory names that do not describe all the facets of the pathway. For instance, the short name "Contaminant on plants" could be perceived to include "Contaminant nursery material" and, to some degree, "Contaminant – Transportation of habitat material", which are separate pathways. One possible improvement, as discussed by the expert team, might be to cross-reference the subcategories, i.e. the description for Contaminant on plants could be "Contaminant on plants that are not part of the nursery trade" (or plants for planting). Other examples might include the contamination of seeds (Seed contaminant subcategory), where the seeds are also food items. This issue is covered, for example, by IPPC, that, according to ISPM 5 (FAO 2015), uses the term "grain" as a commodity class for seeds transported for processing or consumption and not for planting and blurred delimitation of the category "Food contaminant (including of live food)". However, cross-referencing might be a suboptimal approach for dissemination of findings of pathway analyses to public and policy; the pathway subcategories titles need to be sufficiently short to be used widely in figure legends and communication documents. For this reason, each subcategory should also have a concise short description, as well as the detailed description. The concise descriptions should give the most pertinent information while the longer description should have all information required to limit the risk for confusion regarding what is included and what is not.

Some pathways are relatively specific ("Biological control", "People and their luggage/equipment – in particular tourism"), while others are broader and less specific. Examples are the CBD pathway subcategories like "Seed contaminant", "Contaminant on animals (except parasites and species transported by host/vector)" or "Timber trade". These groups include a variety of different sources and vectors that can be controlled at borders and regulated. Specifically, the pathway "Contaminant on animals" is based on a number of activities, mainly related to the breeding of animals and trade with products derived from them. This subcategory applies, for example, to seeds/propagules on the fur or in the digestive tract of live animals, as well as to animal products (or by-products) – for example, on the skin and in the wool. It also includes, for example, transport in bedding. The pathway "Timber trade" includes logs, sawn timber and processed wood products (e.g. furniture) or sawdust and firewood. Similarly, the pathway "Seed contaminant" would be better split into at least two pathways as the risk of introduction differs greatly between contaminants of seeds for planting, compared with contaminants of seed that will be processed for food production (see our comment above and definition of "Food contaminant (including of live food) " or as animal feed.

We are not recommending an increase of the hierarchical levels of the CBD Pathway Classification framework, but to adjust the width of the subcategories and their direct link to vectors and possible legislation management. In many cases there is a residual subcategory "other" (e.g. "Other intentional release", "Other escape from confinement"), so that one possible approach would be to specify and split this residual

Table 5. Summary of some issues (including illustrative examples) and recommendations for changes to the CBD Pathway Classification framework or accompanying guidance document.

Topic	Issues	Example	Recommendation
Modification of subcategories	Pathway subcategory too broad and thus ambiguous	Seed contaminant	Divide into two subcategories: 1. contaminants of seeds for planting, 2. contaminants of seed that will be processed for food production or as animal feed
	Overlap amongst pathway subcategories	Agriculture, Horticulture, Ornamental purpose other than horticulture (horticulture is an industry process compared to ornamental purposes)	Ensure clear definitions, consistent with standard use in other sectors. Classify pathways to horticulture as a branch of agriculture separated clearly from ornamental use.
Revision of descriptions	Short pathway names attributed within the framework are unclear or ambiguous	Contamination on plants	Contamination on plants that are not part of the nursery trade
Allow revisions based on new and emerging pathways	Vector does not correspond to the pathway category	Intentional release in the wild of aquarium kept species is different from unintentional Escape from Confinement.	Assign to the "Release" – Other intentional release or add a new vector category "Release"-aquarium/ terrarium-zoo species
	Biological invasions are dynamic processes and there is a need to update the classification accordingly including emerging pathways	Floating marine litter	Assign floating marine litter to the pathway "Transport – stowaway"
		Bilge waters as a secondary means of transport	Assign to the pathway "Transport – stowaway" other means of transport
		The release of by-catch fish in commercial fishing	Assign to "Transport-stowaway" Angling/fishing equipment" category.

subcategory, limiting the number of unclassified pathways. Adopting a nested structure in the pathway descriptions would need to be reflected in the database structures and most of the data would be available at a less detailed scale.

Furthermore, we found that it is difficult to separate the pathways for "Horticulture" and "Ornamental purposes other than horticulture". The distinction is based on the risk or event of escape from a private garden compared to an escape from horticultural (commercial, industrial) facilities. Indeed, although the risk is vastly different, based on information available, there is often the possibility to use only a single pathway, that corresponds to Escape from culture/captivity: gardening. In the guidance document (Harrower et al. 2017), there is some overlap in defining "Agriculture", "Horticulture" and "Ornamental purpose other than horticulture". A possible solution could be to apply the definition from the ISHS (International Society for Horticultural Science; https://www.ishs.org/) for horticulture as a branch of agriculture and to consider AIPH (International Association of Horticultural Producers; http://aiph.org/)

for ornamental horticulture, traditionally considered as a branch of horticulture. This is supported by the traditional view that vegetables are included in horticulture and not in agriculture. In addition, it is certainly useful to consider at least two different scales of these subcategories, to differentiate between the industrial and home use of agricultural and horticultural crops and ornamental plants. Many typical horticultural crops in Europe have a very low risk of escape, regardless of whether they are cultivated in home gardens or intensively over large areas (Pergl et al. 2016b). In contrast, a large number of ornamental species might easily escape from gardens, while they might be more safely kept in dedicated commercial horticultural facilities by responsible growers (Anderson et al. 2006; Bayón and Vilà 2019).

There was also some confusion in the use of the high level categories Stowaway and Contaminant. This appeared to be remedied following detailed consideration of the definitions within the Guidelines. On the one hand, experts agreed that, where the alien species has a trophic or abiotic relationship to a specific substrate, meaning it cannot survive without it, it is clearly a Contaminant. The uncertainty arises where an alien species is typically associated with a substrate, but is able to survive away from it. These two subcategories are distinguished by the nature of the contaminated substratum; if the contaminated substratum is itself a commodity and a vector, then the assigned pathway should fall in the Contaminant category. However, if the contaminated substratum is only a vector (physical or biological), then the assigned pathway should fall in the Stowaway category.

Parasitic alien species, whether in or on plants or animals, were mostly easy to categorise. The categories of pathways related to parasites, however, appear to be less useful in terms of managing the IAS, without the information on pathways applying to the host species (see, for instance, Navajas et al. 2012). Harrower et al. (2017) suggested that subcategories, such as "Contaminant on animals", "Parasites on animals", "Contaminant on plants" and "Parasites on plants", should all be renamed by replacing the "on" in the title with "of", for example, "Contaminant of animals". This would improve clarity by ensuring these subcategories refer to species transport on or in the species. As it currently stands, the title implies that the subcategories should only be used for species that are transported externally on the plant or animal.

In aquatic environments, plastics or other human-made floating materials can travel considerable distances on ocean currents and are capable of transporting and spreading reproductively viable biota (see review in Rech et al. 2016). For example, following the Japanese tsunami in 2011, colonies of living bryozoan *Schizoporella japonica* (alive with embryos) were found on the Hawaiian Islands and in North America after traversing the Pacific Ocean (McCuller & Carlton, 2018). It is, therefore, possible that such colonies may develop on natural and artificial objects which may become flotsam, providing a pathway of introduction and spread. With an increase in drifting marine litter, this potential vector is becoming increasingly prevalent (Barnes 2002; Ivkic et al. 2019). Whilst drifting litter is transported by natural forces (pathway Unaided), it is considered that the presence of anthropogenic marine litter is a human influence, without which fouling species would not be able to make use of prevailing currents

to spread rapidly. Therefore, we think that the pattern fits better to the "Transport-stowaway" – other means of transport as a primary pathway.

Bilge waters are another issue for the aquatic environment and identified as an important vector. The metabarcoding analysis of 23 bilge samples collected from yachts and motorboats operating commercially and recreationally in two boating hubs in New Zealand's South Island, led to the identification of five alien species, including the polychaete, *Boccardia proboscidea* (Fletcher et al. 2017). Even though they are in the current CBD Pathway Classification framework categorised to ballast water, due to their different character and aspect of regulation, they better fit to "Transport-stowaway: other means of transport".

The release of by-catch fish in commercial fishing can be a relevant pathway of secondary spread. This will depend on fishing and discard practices, with the highest risk from bottom trawlers. Survival rates of discarded fish (e.g. *Plotosus lineatus* in the Mediterranean Sea) are unknown, but can be high for some species. Such secondary spread was classified by Galanidi et al. (2019) as "Release in nature: other intentional release – fisheries discards", but fits also to the "Transport-stowaway: Angling/fishing equipment" category.

Lack of data leading to low confidence

Assessments of presence and impact of IAS is always affected by the uncertainty in available data (Probert et al. 2020). The lack of available information on introduction and secondary spread pathways for a high number of species is problematic. For example, a number of alien species have been recorded only a few times. It is often challenging to establish whether this pattern is the result of independent primary introduction events or of secondary spread after a single introduction. However, in some cases genetic analyses have provided evidence of independent introductions, for example, in insects or plants (Bras et al. 2019; Neophytou et al. 2019). It is likely that the importance of the pathways within stowaways has been underestimated in terrestrial arthropods because a large number of the categorisations within our exercise were based on the biology of the transported species and their host organism, especially for those associated with plants, but only a few of these arthropods were actually intercepted along the putative pathways (Eschen et al. 2015). By contrast, transport as hitchhikers in vehicles or containers is increasingly observed (Rabitsch 2010). A number of experts flagged that species that contaminate consignments, such as wood furniture or woollen products, are not easily assigned to the pathway descriptions and thus not easily categorised.

The biogeographic status of many species remains uncertain. These species are flagged as 'cryptogenic' when there is medium uncertainty about their origin, that is, whether they are native or alien or 'data deficient' when there is high uncertainty on their biogeographic status (Essl et al. 2018). For such cryptogenic or data deficient species, it is counter-intuitive to assess primary pathways (if we knew that they were introduced with a specific pathway, we would be certain of their alien status). For these species, it makes sense to assess only the secondary spread pathways.

Additional comments for policy and pathway management

One of the greatest challenges experienced by the project team in assigning pathways based on the CBD Pathway Classification framework was ensuring the accurate classification of intentional releases from pathways classified only amongst those listed as “Escape from confinement”. A notable example is the “Pet/aquarium/terrarium species (including live food for such species)”. Indeed, this subcategory has been systematically used also to cover species which were introduced in a country intentionally for such purpose, but that either escaped in the environment accidentally or were released intentionally (for example, in the case of animals abandoned). Similarly, this may be the case also with other subcategories, such as “Live food/bait”, “Horticulture”, “Ornamental purpose other than horticulture” etc. (for example, in the case of live baits or cut plants dumped in the environment).

As stated in the guidelines on the CBD Classification Pathway framework (Harrower et al. 2017), the rationale behind the choice of a subcategory should be the primary intention of introduction, because this is of value in informing relevant stakeholders (and consequently has clear implications for the management of pathways). However, this approach was not always considered appropriate. This situation can be exemplified through one of the pathways considered of increasing concern: the intentional release of aquarium species into the wild (Zenetos et al. 2016), in contrast to cases of actual escapees from aquaria, for example, the escape of *Caulerpa taxifolia* from the Monaco aquarium and its introduction to the Mediterranean Sea (Jousson et al. 1998). Although intentional releases of aquarium species should be assigned in the “Release in nature” category under the CBD Pathway Classification framework, they are currently assigned as “Escape from confinement: Pet/aquarium/terrarium species (including live food for such species)”. The rationale was that these species were initially imported for a confined environment (aquarium) and then introduced into the wild ‘escaping from the confinement’. However, aquarium species are most often intentionally dumped into the waters and should, therefore, be assigned to the “Release” pathway category. Recognition of the importance of this pathway of introduction would facilitate appropriate measures including communication campaigns, for example, targeting citizens and so preventing such releases. Typical measures relevant for the “Escape” category (unintentional) mainly focus on involving the relevant stakeholders, inviting them to adopt voluntary codes of conduct or adopting rules for limiting importation/trade. On the other hand, measures relevant for the “Release” category (intentional) mainly focus on public awareness or the registration of animals kept in captivity. Raising public awareness is critical for the management of marine IAS (Giakoumi et al. 2019) and could be undermined if IAS released by aquarium hobbyists are classified as escapees. The same considerations are relevant to the release of aquatic or terrestrial species for religious ceremonies. The release of captive animals to gain spiritual favour is a widespread religious practice, especially amongst Buddhists and Taoists (Wasserman et al. 2019; Magellan 2019). For all these cases of pet/aquarium/terrarium species intentionally released in the wild, we suggest a new subcategory “Release in nature: Pet/aquarium/terrarium species” to be added under the “Release” pathway category. In this way, it will be possible to differentiate classification and

proposed management measures between intentional releases and unintentional escapes of such species. Nevertheless, we recognise that implementing such change may alter the overall rationale behind the CBD Pathway Classification framework and relevant guidance document by Harrower et al. (2017). Therefore, it would require a systematic, measured and analytical revision of the classification system, otherwise there is a risk that there could be greater confusion than the change would aim to solve.

Conclusions

A pathway framework needs to be based on sound science while flexibly accommodating the dynamic nature of biological invasions to satisfy policy and practitioner needs underpinning research and management of IAS. It is important that the compilation of information, such as pathways of introduction for alien species, follows global standards (see, as example, the Darwin Core Initiative; Groom et al. 2019) to ensure wide use and applicability. However, in developing a standard, it is also important to consider the social, spatial and temporal variation inherent to the process of biological invasions (see example for WRA; Gordon et al. 2010). The CBD Pathway Classification framework provides a robust and adaptable approach for assigning pathway information across taxonomic/environmental groups and has been a first ambitious attempt to unify approaches at the global level. It is critical that the published guidance (Harrower et al. 2017), which provides supporting information, is globally used and tested to ensure consistency of application across information systems.

It is essential that the experts, who assign pathways, openly share information and provide updates to the CBD Pathway Classification framework guidance to reduce ambiguity. To date, the broad hierarchical CBD Pathway Classification framework provides a tool which can be applied in diverse contexts, enabling rapid analysis of changing patterns and trends in biological invasions to be communicated rapidly and transparently, so that periodical updates will increase its value and effectiveness over time. However, it is essential that modifications are agreed collaboratively and communicated to everyone using the framework to reduce subsequent inconsistencies in use. We describe potential discrepancies and potential solutions to provide an updated CBD Pathway Classification framework (Table 5). The major issue simply relates to better description of individual pathway subcategories with global relevance. Our analysis, covering a large geographic area and different taxonomic groups and environments, highlights the value and applicability of our suggested modifications.

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Supplementary material 1

Table S1

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Data type: pathway data

Explanation note: Assessed species with assignment to CBD Pathway Classification subcategories and the relevant references. P indicates primary introduction and S secondary spread. Subcategories: **Release** 1 Biological control, 2 Erosion control/ dune stabilisation (windbreaks, hedges, …), 3 Landscape/flora/fauna "improvement" in the wild, 4 Fishery in the wild (including game fishing), 5 Hunting, 6 Introduction for conservation purposes or wildlife management, 7 Release in nature for use (other than above, e.g. fur, transport, medical use), 8 Other intentional release; **Escape** 9 Agriculture (including Biofuel feedstocks), 10 Farmed animals (including animals left under limited control), 11 Forestry (including afforestation or reforestation), 12 Fur farms, 13 Aquaculture / mariculture, 14 Botanical garden/zoo/aquaria (excluding domestic aquaria), 15 Pet/aquarium/terrarium species (including live food for such species), 16 Horticulture, 17 Ornamental purpose other than horticulture, 18 Research and ex-situ breeding (in facilities), 19 Live food and live bait, 20 Other escape from confinement; **Transport – Contaminant** 21 Contaminant nursery material, 22 Contaminated bait, 23 Food contaminant (including of live food), 24 Contaminant on animals (except parasites, species transported by host/vector), 25 Parasites on animals (including species transported by host and vector), 26 Contaminant on plants (except parasites, species transported by host/vector), 27 Parasites on plants (including species transported by host and vector), 28 Seed contaminant, 29 Timber trade, 30 Transportation of habitat material (soil, vegetation,…); **Transport – Stowaway** 31 Angling/fishing equipment, 32 Container/bulk, 33 Hitchhikers in or on aeroplane, 34 Hitchhikers on ship/boat (excluding ballast water and hull fouling), 35 Ship/boat ballast water, 36 Ship/boat hull fouling, 37 Machinery/ equipment, 38 People and their luggage/equipment (in particular tourism), 39 Organic packing material, in particular wood packaging, 40 Vehicles (car, train, …), 41 Other means of transport; **Corridor** 42 Interconnected waterways/basins/seas, 43 Tunnels and land bridges; **Unaided** 44 Natural dispersal across borders of invasive alien species that have been introduced through pathways 1 to 5.

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